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Report on RF field perturbations of Tevatron cavity caused by mechanical vibrations of the cavity.

RF field perturbation measurements was started in August 2002. For RF field amplitude detectors and phase signal I used HP49410A vector signal analyzer. Measurement of 16 amplitude detector, 8 local phase detector signals and 2 global phase loop signals shows presence of high noise level in 30-40Hz frequency range, fig1. Phase noise in range from 0Hz up to 34Hz (synchrotron frequency of accelerated beam in Tevatron) will affect to longitudinal beam stability. It was proposed that this noise caused by mechanical vibrations of the central electrode of the cavity. HFSS RF simulations shows high sensitivity of RF field in the cavity on position of the central electrode, fig17. Ivan Gonin's Ansys simulations shows 4 mechanical resonance's in range 35-38Hz and confirm this supposition, fig16. The results I reported in October 23 2002 meeting.

It was decided to make additional mechanical vibrations and measurements during January shutdown of Tevatron. Cristian Boffo, TD, helpfully provided with horizontal and vertical geo sensors HS1 for mechanical vibrations measurements. I prepared hardware – LaptopPC with 16 channel DAQ-card installed and software – Lab View programs for gathering and analyzing data. Gennady Romanov take a lot of care about getting access to Tevatron tunnel for us. John Reid take all care with different regimes operation of RF stations.

Vladimir Shiltsev proposed to check geo sensors and compare with calibrated geo sensor CM-3KB. The results of calibration measurement shown in fig2. For this measurement CM-3KB sensor was installed in my office table and 2 vertical sensors HS1 on CM-3KB sensor top plate.

Because at beginning there was no access to tunnel to install sensors and make measurements, we started measuring mechanical vibrations on prototype cavity installed in "cave" in building MI60, fig3. It was nice also to test newly developed software. Measurements was made in 21-27 January 2003 by Cristian, Gennady, John and me. Results shown in fig4.

In 28-30 January we have access to tunnel to install sensors and measure on station2, fig5. Station2 was proposed by John as a one of most noisy stations. In last day, 4 Geo sensors was properly installed to cavity and connected to cables comes upstairs to RF gallery.

After discussion with Valeri Lebedev and Vladimir Shiltsev was decided to make additional measurements in different frequency of reference line. John and I make these measurements in 02 February 2003.

In this report last results and of measurements and analysis.

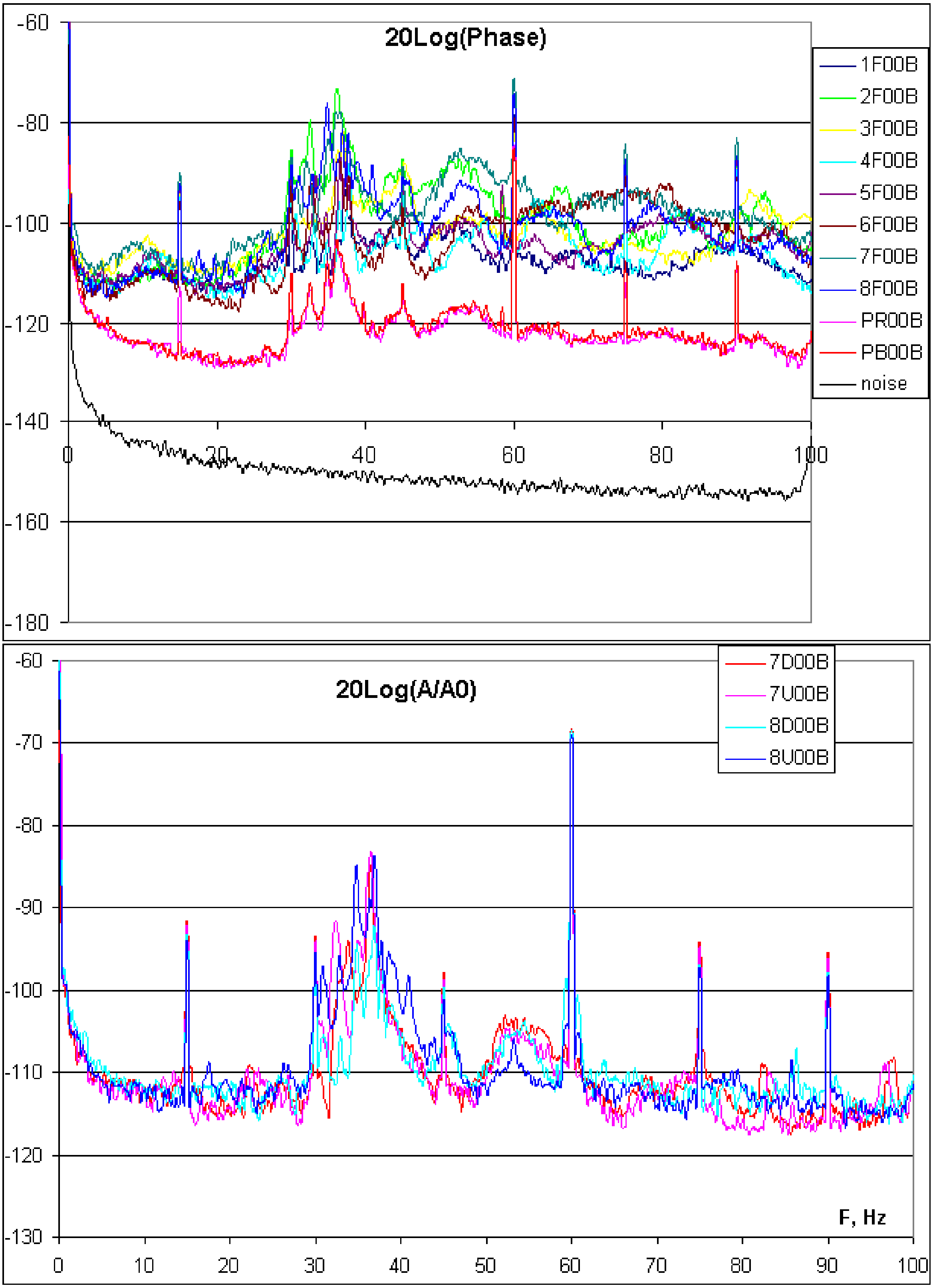


Fig 1. Tevatron stations RF noise measurements. All (global and local phase and local amplitude) loops active.

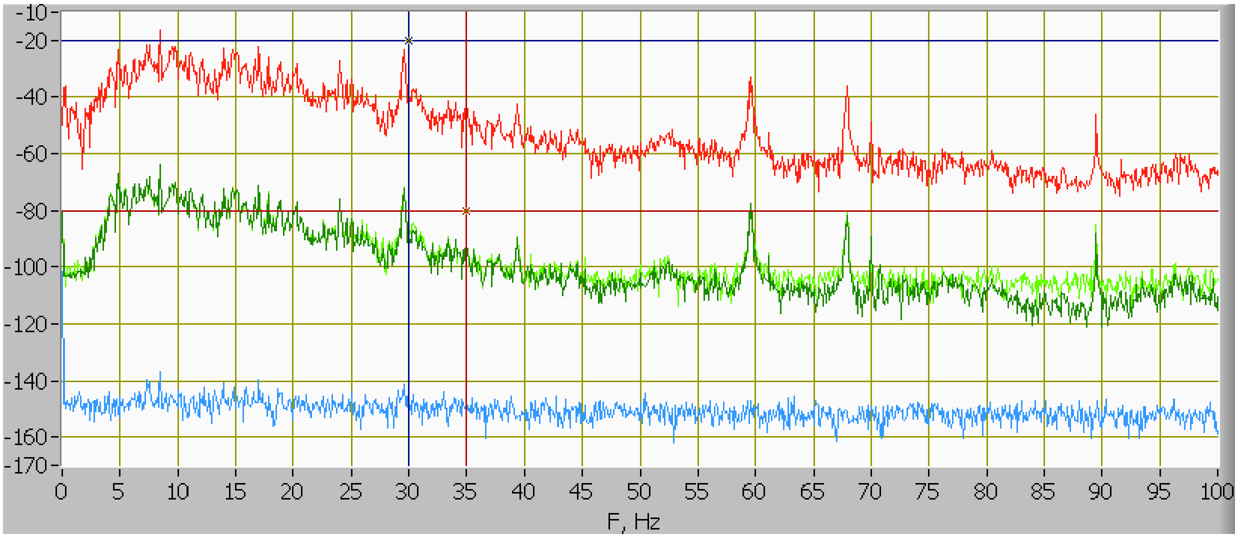


Fig 2a. Spectrum. Red line CM-3KB sensor. Green and dark green lines HS1 sensor. Blue line grounded input – instrumental error.

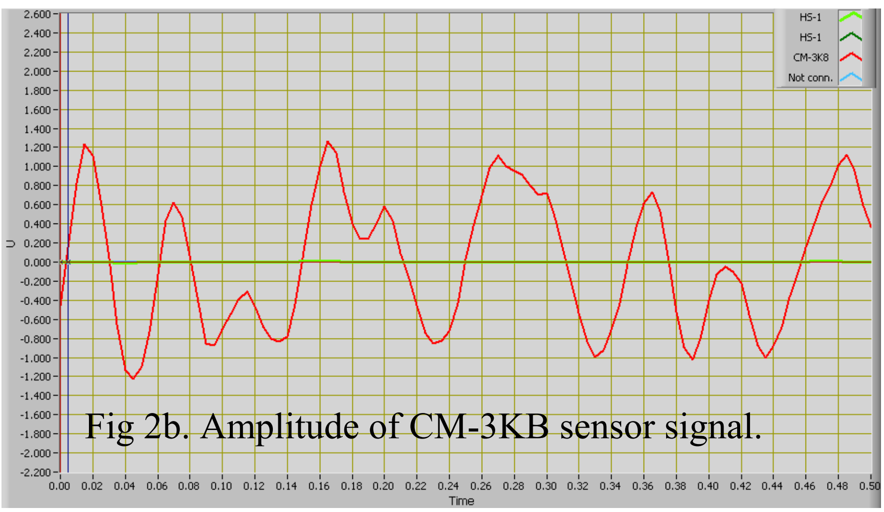


Fig 2b. Amplitude of CM-3KB sensor signal.

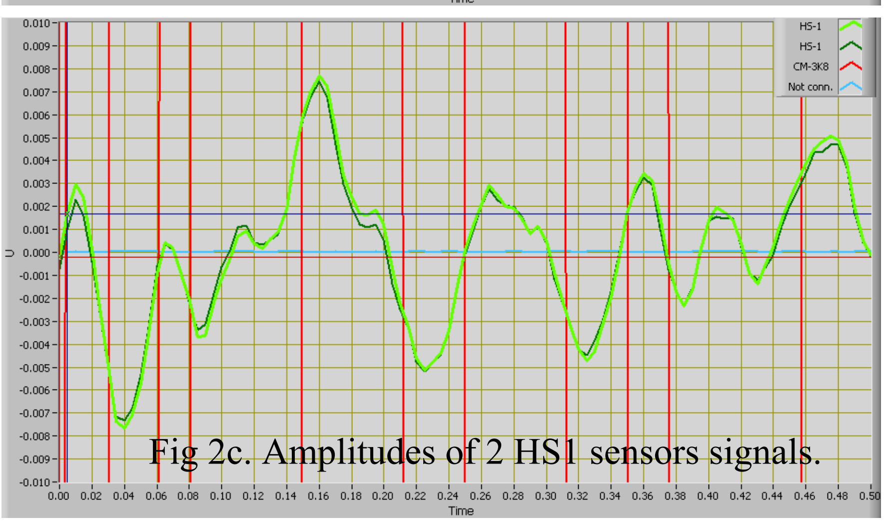


Fig 2c. Amplitudes of 2 HS1 sensors signals.

Sensors sensitivity: CM-3KB: 8.3V/(mm/sec).

HS1: 1.15V/in/sec or 45V/(m/sec).

Difference in sensitivity 45.3 dB.

Measured difference 47dB in frequency range 10-100Hz.

Fig 2. Calibration measurement.

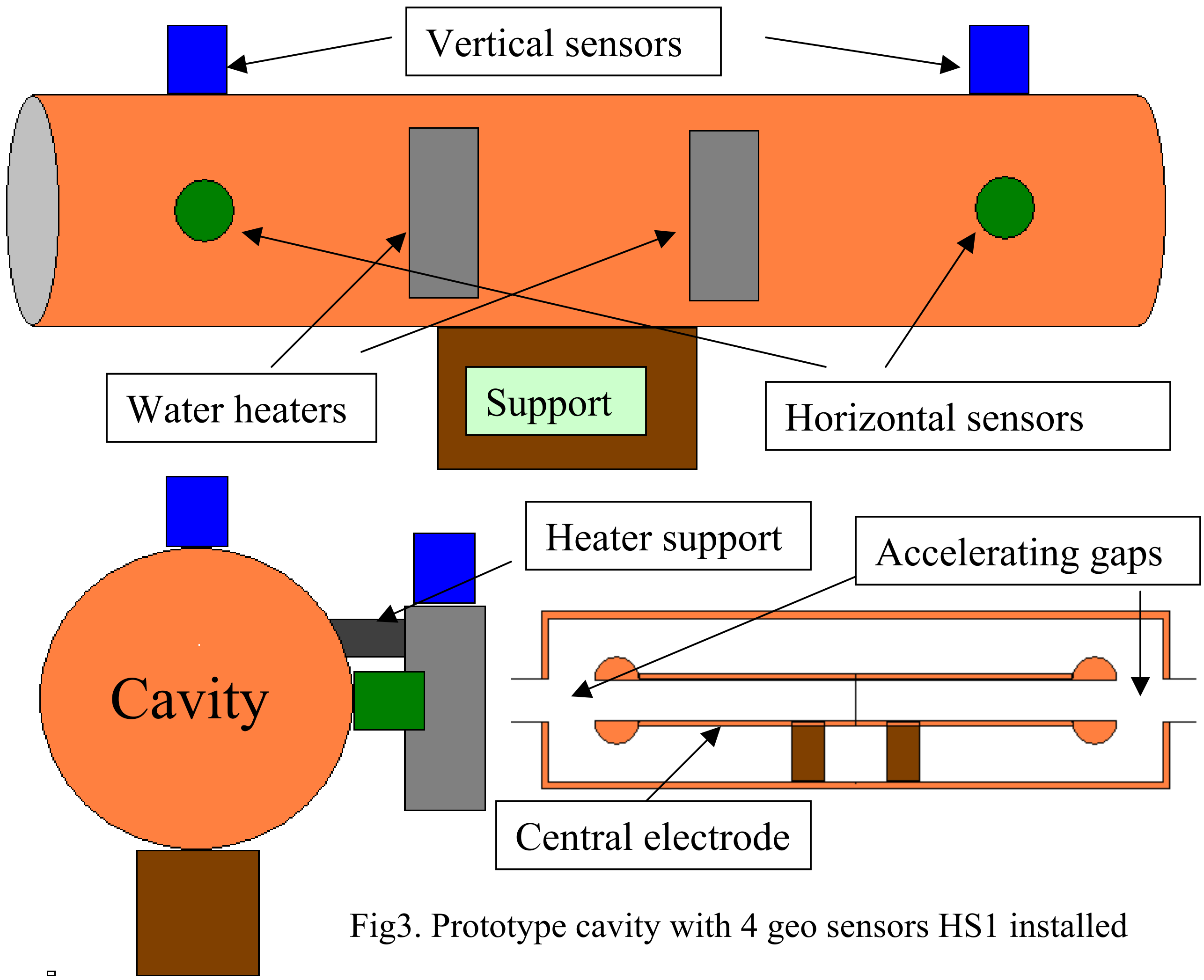


Fig3. Prototype cavity with 4 geo sensors HS1 installed

2 vertical geo sensors HS1 installed in top of the cavity in RF peak-up antenna plane. 2 horizontal sensors HS1installed horizontally on flange opposite RF peak-up antenna plane. Cavity installed in car and therefore support system very soft.

This cavity has 2 cooling water systems. Outer cooling loop consist spirally brazed pipes outside of the cavity. 2 in parallel inner cooling loops, each consist 1 water heater and water channels in central electrode of the cavity.

Water heaters attached to cavity through rigid support. If heaters is additional source of vibrations, it should increase vibrations in cavity.

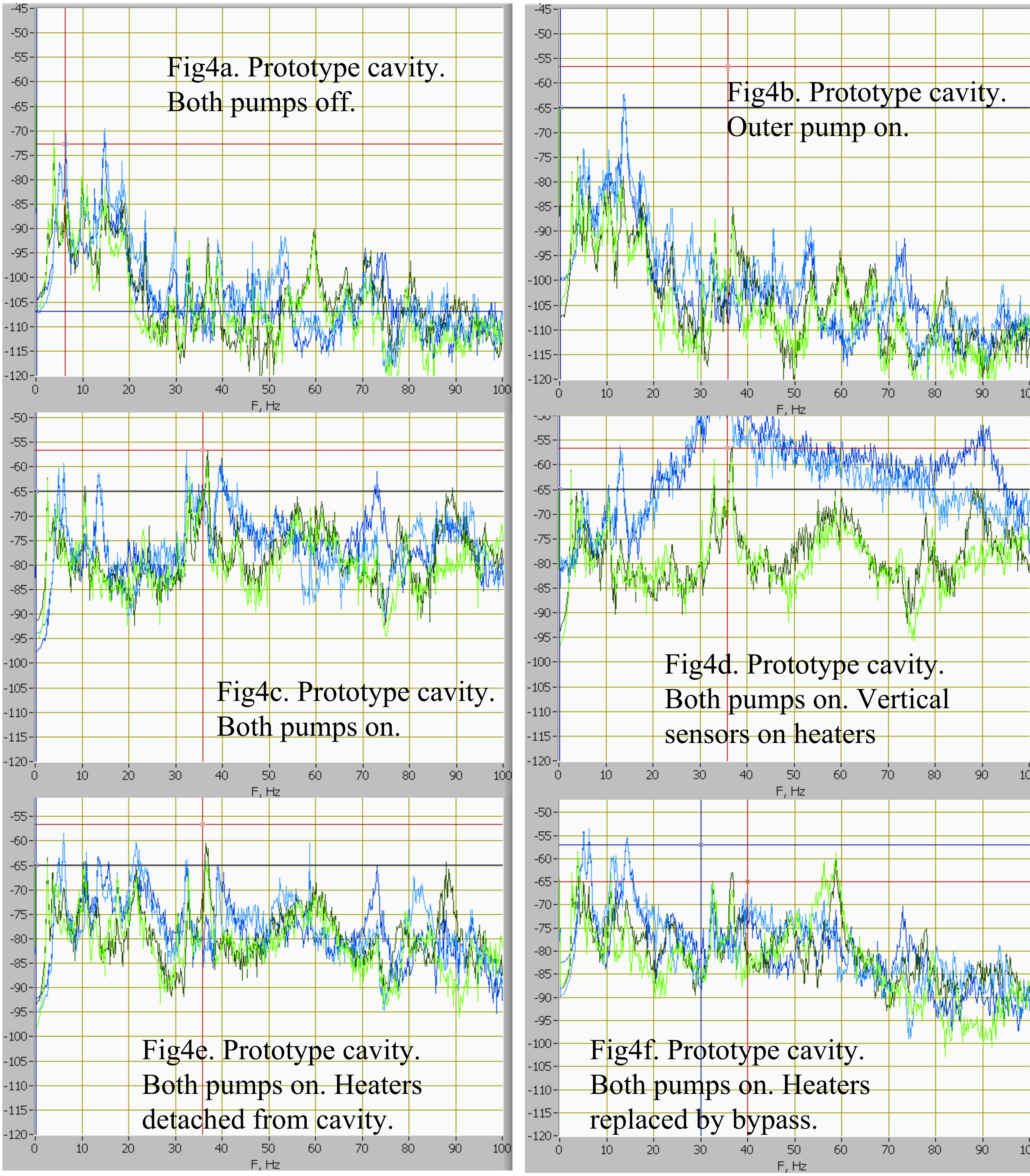


Fig4. Prototype cavity mechanical vibrations measurements. In frequency range 25-40 Hz vibrations on pumps more than 10 dB higher than in cavity surface. When water heaters detached from cavity vibrations in 32 Hz decreased by 8dB and after replacing by bypass even 10dB. It means that water heaters increased mechanical vibrations.

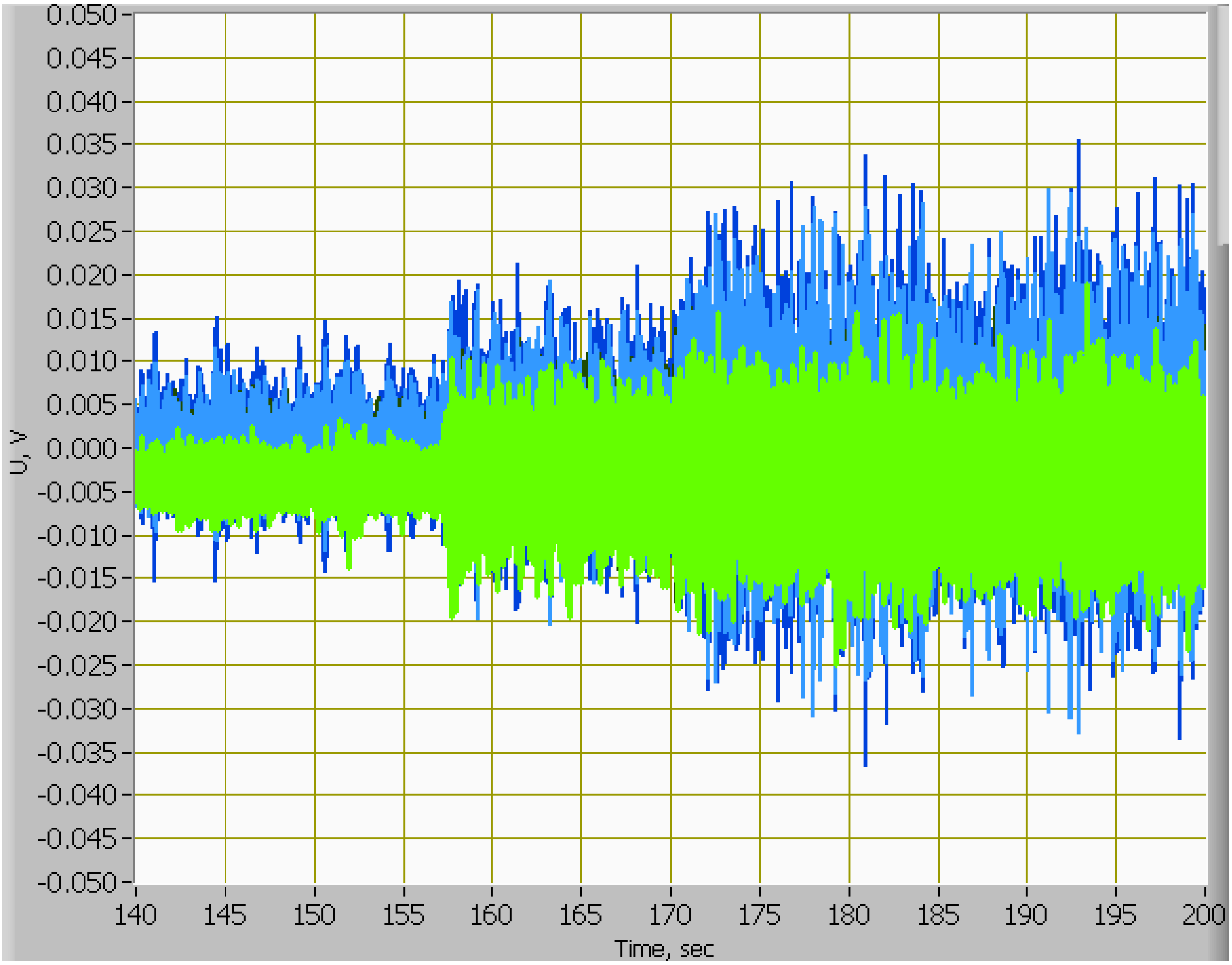


Fig 5. Station2 RF cavity mechanical vibrations measurement. Geo sensors signals during switching on water pumps.

In Tevatron RF stations water cooling system similar to test cavity cooling system except that outer and inner cooling connected in parallel. And also cavity support system completely different. Comparison of water pumps off case for test cavity (fig4a) and Station2 cavity (fig6a) shows presence of high level of mechanical vibrations in range 15-100Hz in Tevatron tunnel.

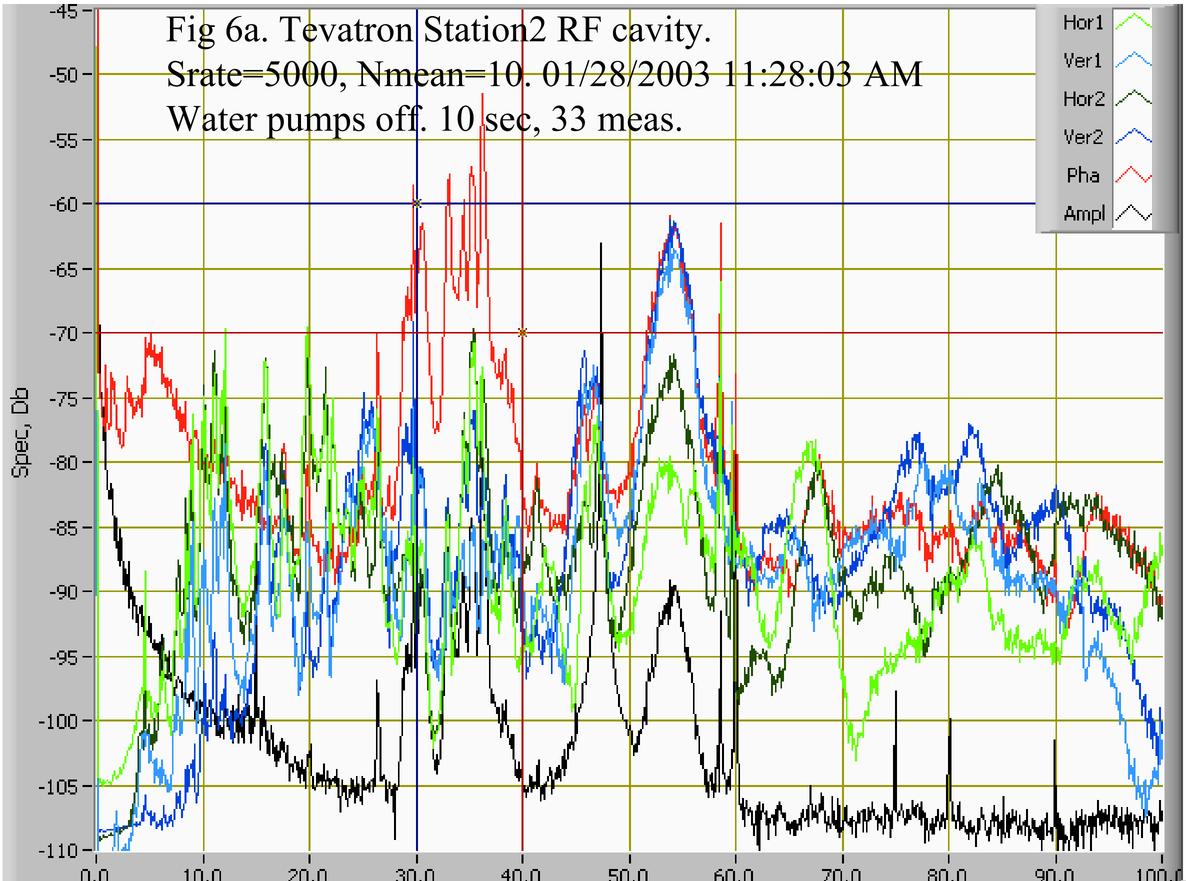


Fig 6a. Tevatron Station2 RF cavity.
Srate=5000, Nmean=10. 01/28/2003 11:28:03 AM
Water pumps off. 10 sec, 33 meas.

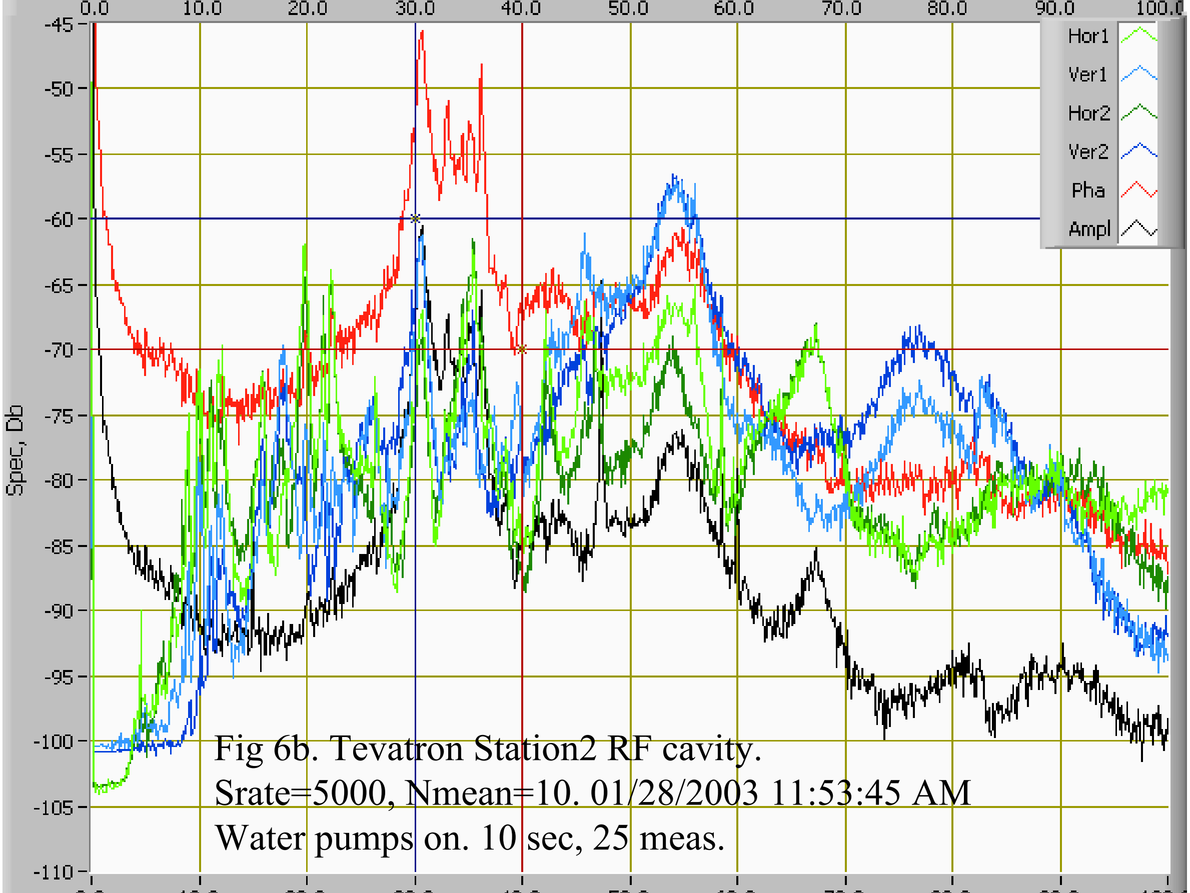


Fig 6b. Tevatron Station2 RF cavity.
Srate=5000, Nmean=10. 01/28/2003 11:53:45 AM
Water pumps on. 10 sec, 25 meas.

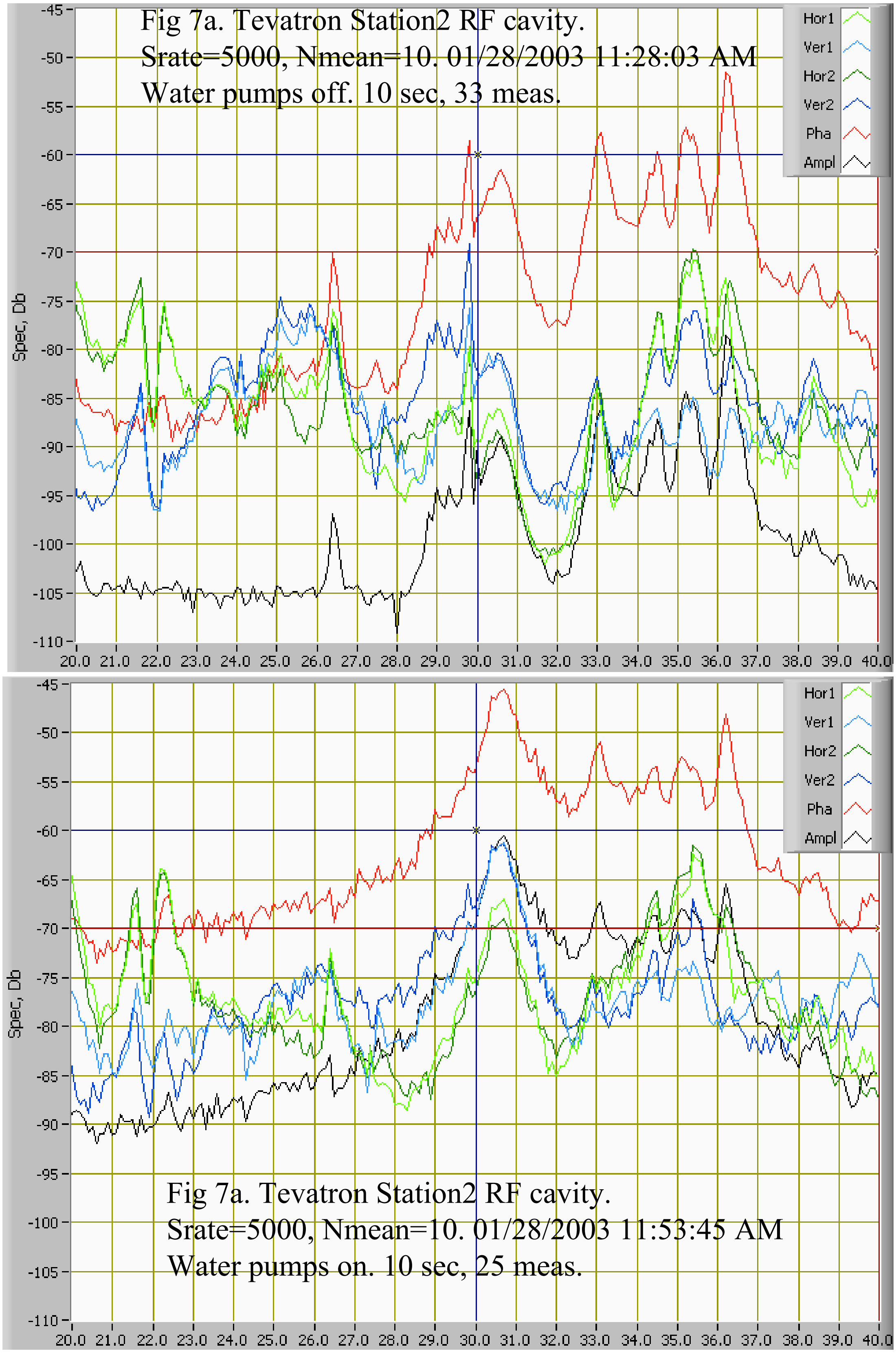
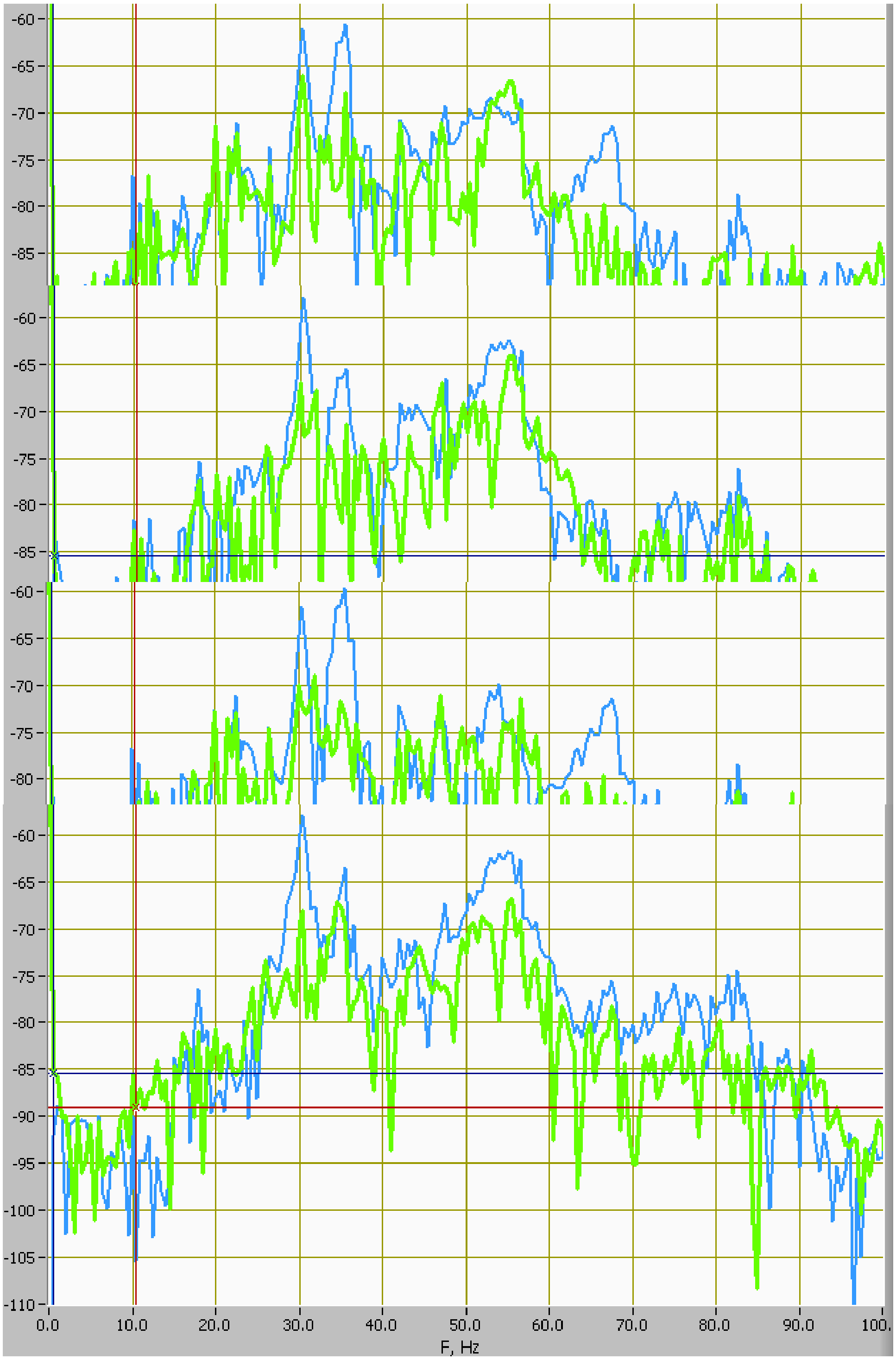


Fig 7. Comparison of water pumps off and on cases in range 20-40Hz
For F=31Hz. After pumps on amplitude +30dB, phase +13dB.



Amplitude detector and horizontal 1.

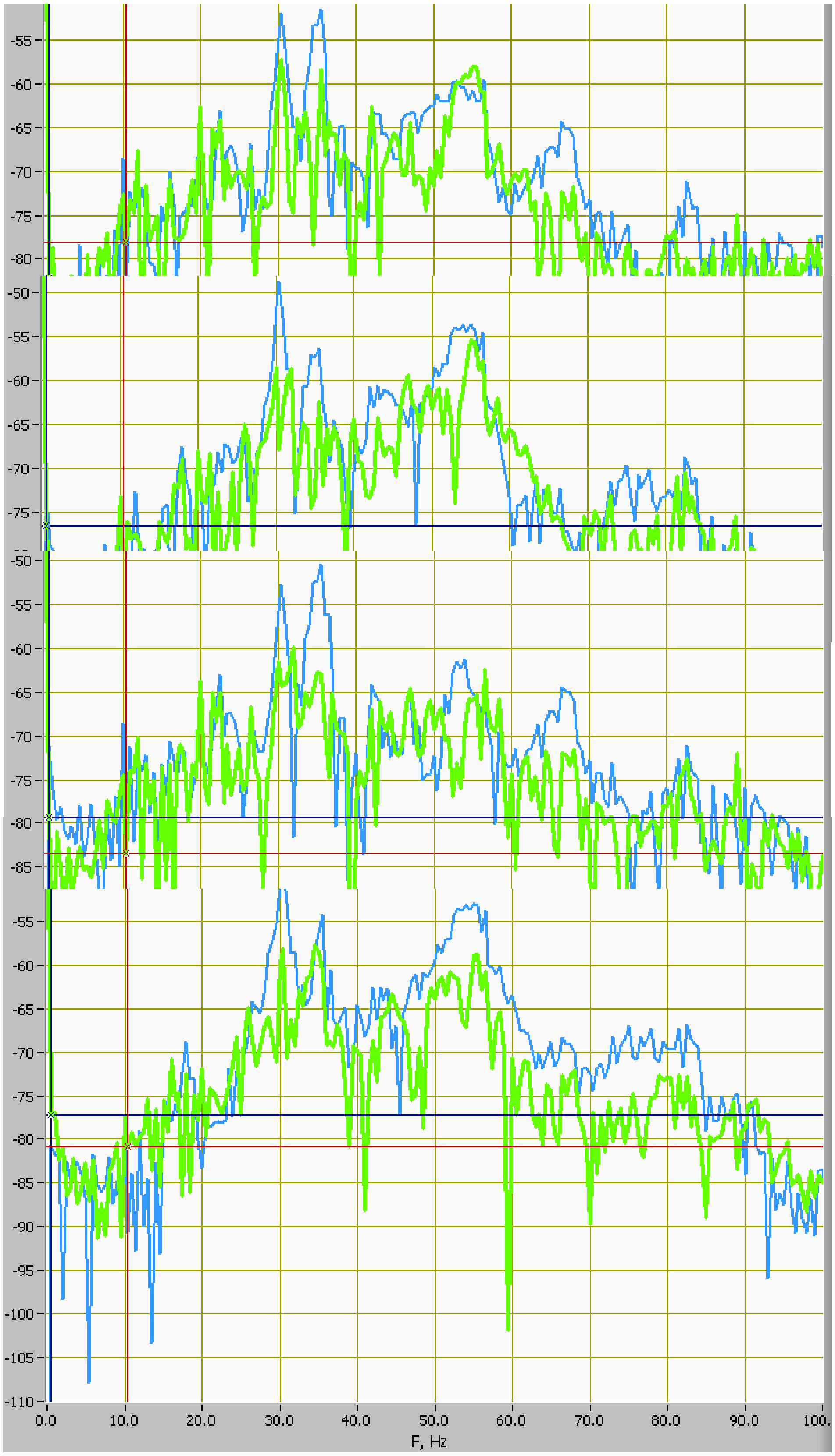
Amplitude detector and vertical 1.

Amplitude detector and horizontal 2.

Amplitude detector and vertical 2.

Fig8.Cross power spectrum (v^2rms) between amplitude detector signal and Geo sensors signals.

At 30 Hz better correlation with vertical and at 33Hz better correlation with horizontal sensor signals and amplitude detector signal. Ansys simulations also gives minimal frequency mode for vertical vibrations, fig16.



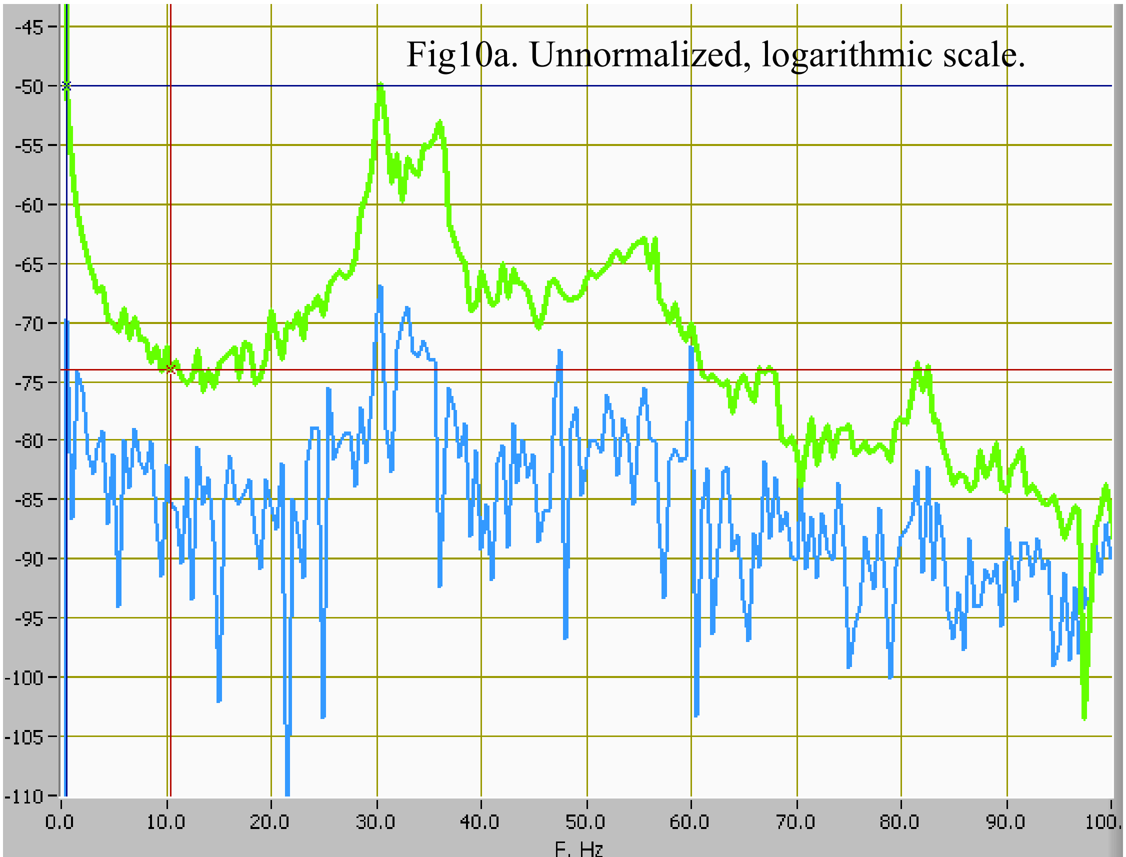
Phase detector and horizontal 1.

Phase detector and vertical 1.

Phase detector and horizontal 2.

Phase detector and vertical 2.

Fif9. Cross power spectrum (v^2rms) between phase detector signal and Geo sensors signals. At 30 Hz better correlation with vertical and at 33Hz better correlation with horizontal sensor signals and phase detector signal.



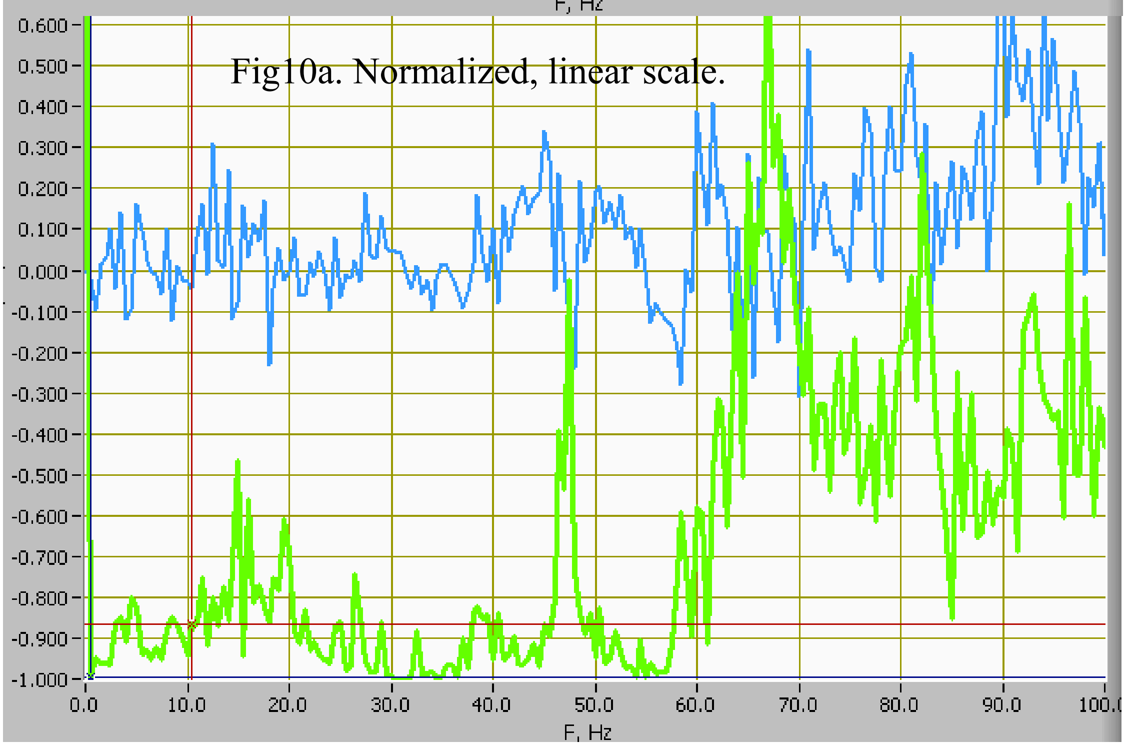
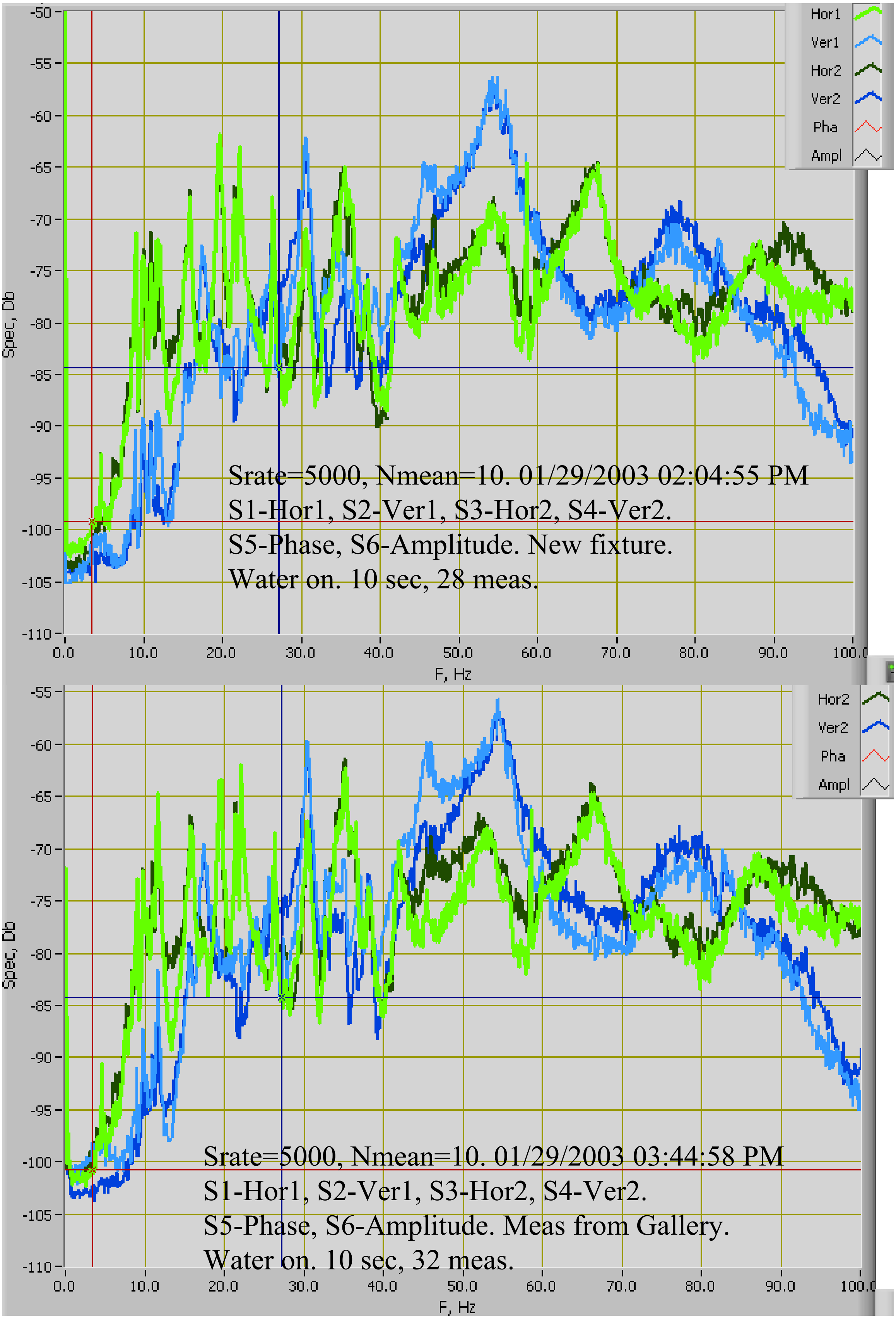
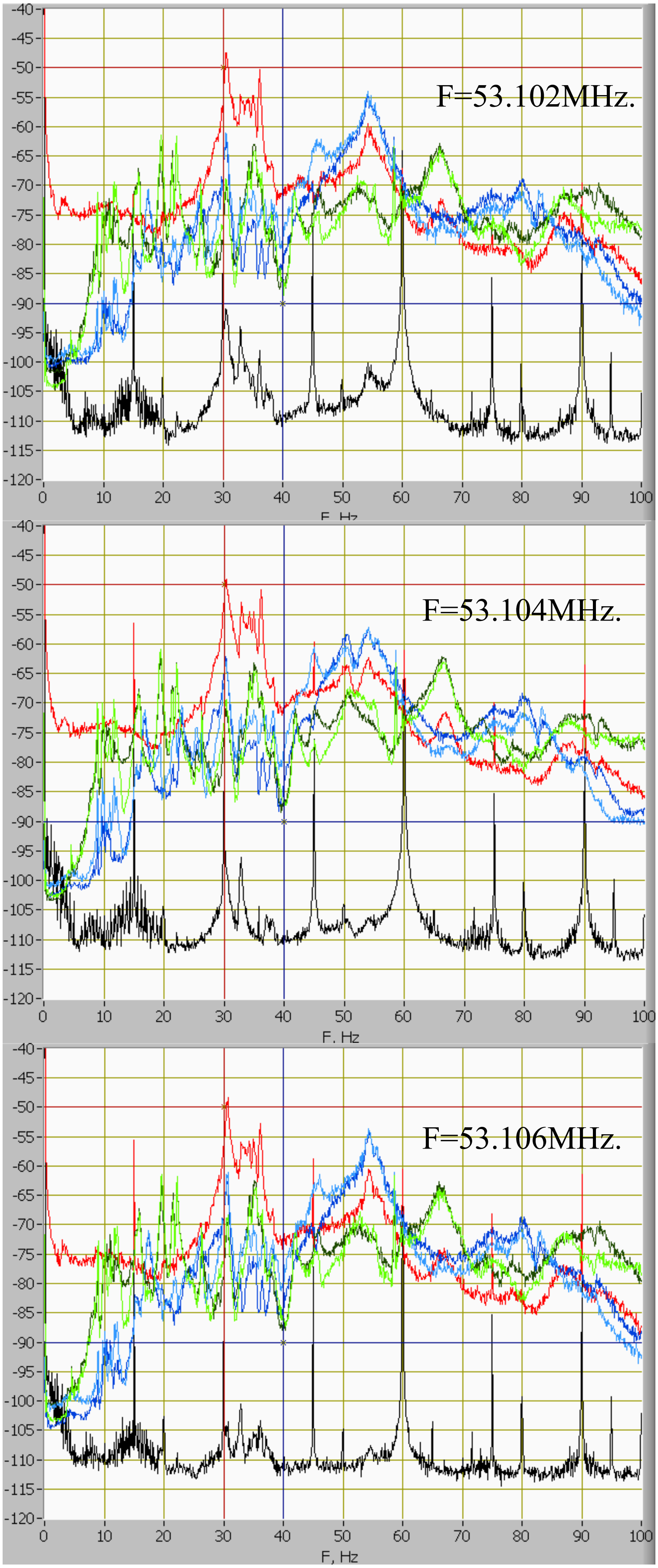


Fig10. Cross power spectrum (v^2rms) between phase detector and amplitude detector signals. It shows good anticorrelation in range 0-60Hz.



Fif11. Comparison measurements in tunnel in gallery.
Spectrums are similar.



Fif12. Station2 in high RF power, accelerating field 166kV per gap. Nominal gap field is 290kV.

Measurements at different RF frequency and the same cavity temperature.

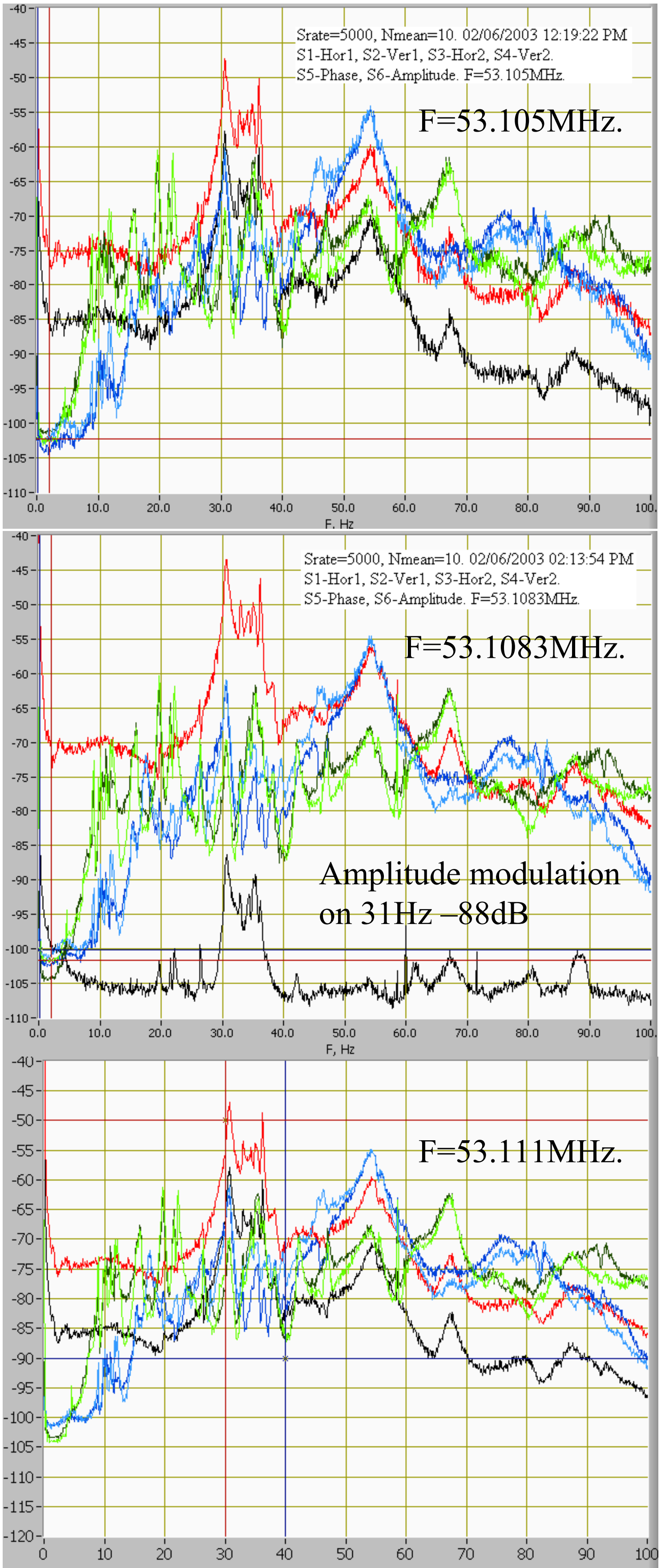


Fig13. Station2 in low RF power. Measurements at different RF frequency and the same cavity temperature.

These measurements shows dependence of amplitude signal spectrum from RF field frequency. From HFSS simulations (fig17) it is a result of cavity resonance frequency modulation caused by asymmetry central electrode position in the cavity.

Comparison of high power (fig12) and low power (fig13) cases shows that amplitude loop of the cavity reduce amplitude modulation of the RF field in cavity. But add modulation at 15Hz and harmonics.

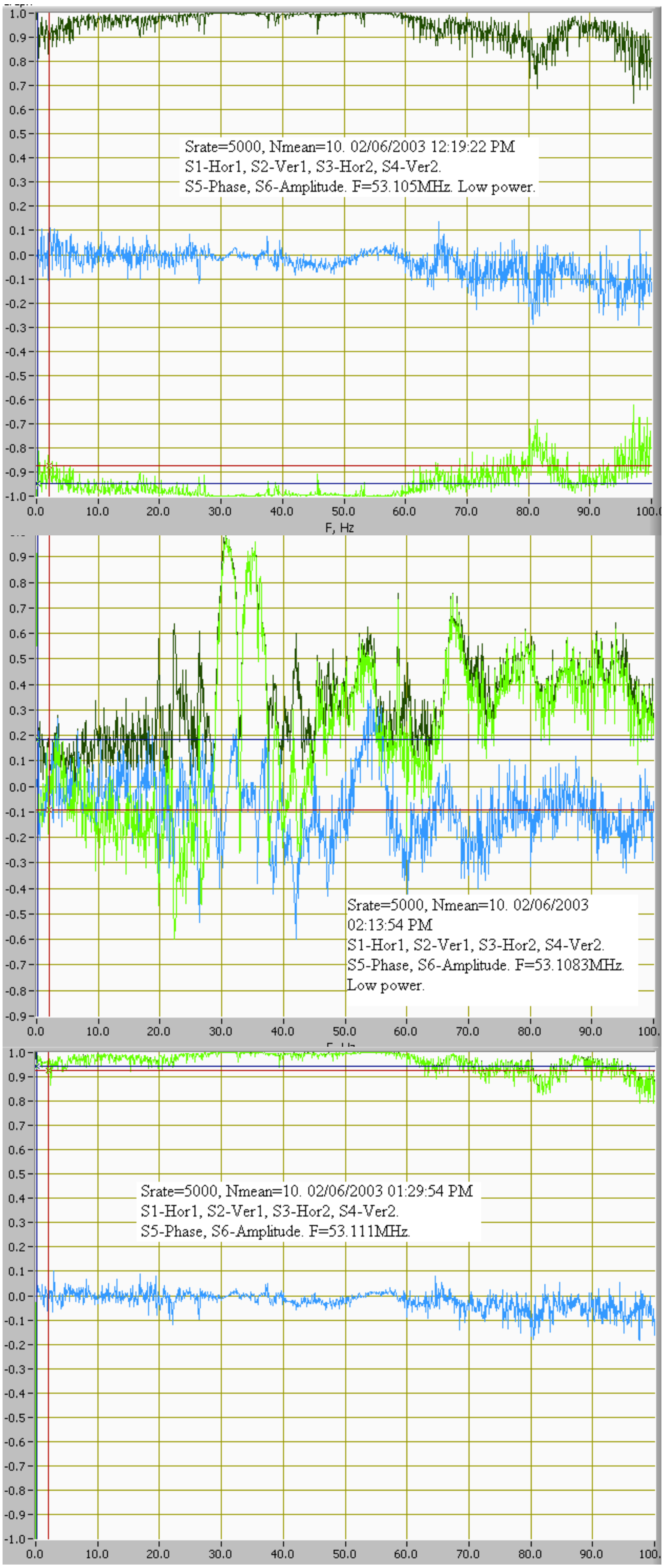


Fig14. Normalized cross power spectrum between phase detector and amplitude detector signals for different RF frequency at the same temperature of cavity.

Green line – real part, blue line – imaginary part, dark green – absolute value

In agreement with fig18 for lower RF frequency real part –1, because curves in Fig18a and fig18b have different sign of slope.

For higher RF frequency real part 1, because curves in Fig18a and fig18b have same sign of slope.

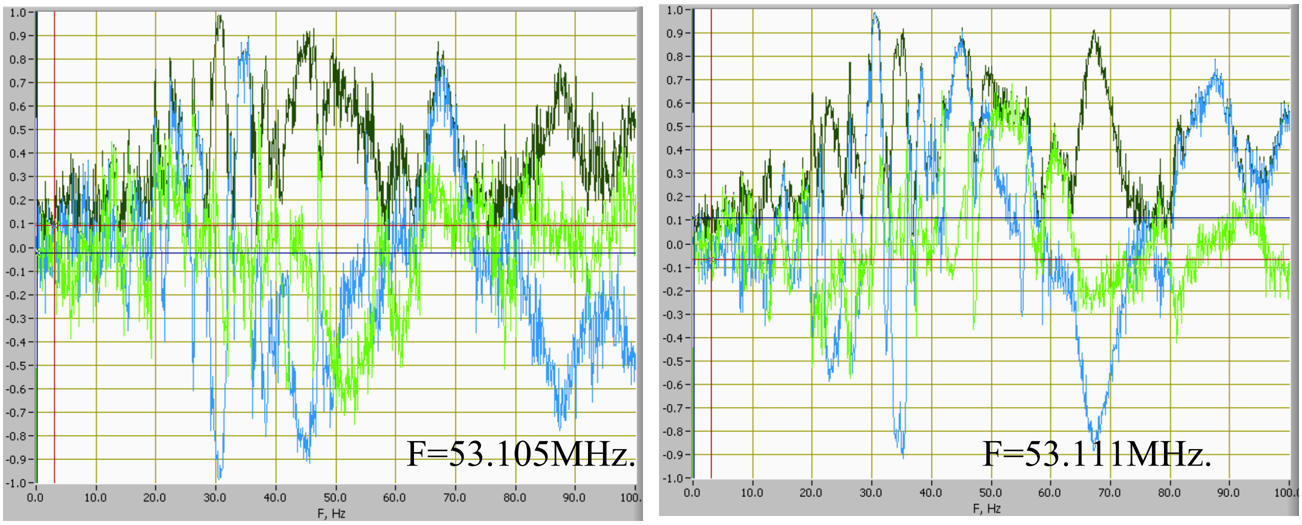


Fig15. Normalized cross spectrum for horizontal sensor1 and amplitude detector signal. Green line – real part, blue line – imaginary part, dark green – absolute value. At central electrode mechanical resonance 31Hz imaginary part equal to 1 for lower RF frequency or –1 for higher RF frequency. Imaginary part because Geo sensor sensitive to movement but not displacement.

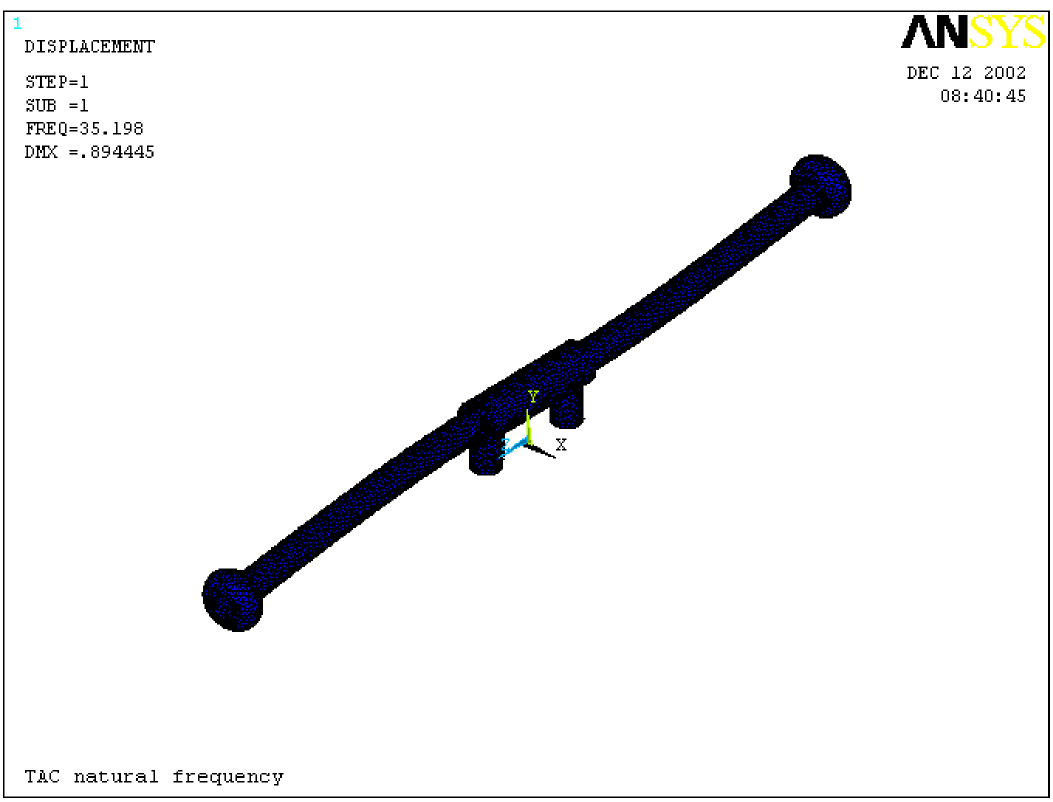
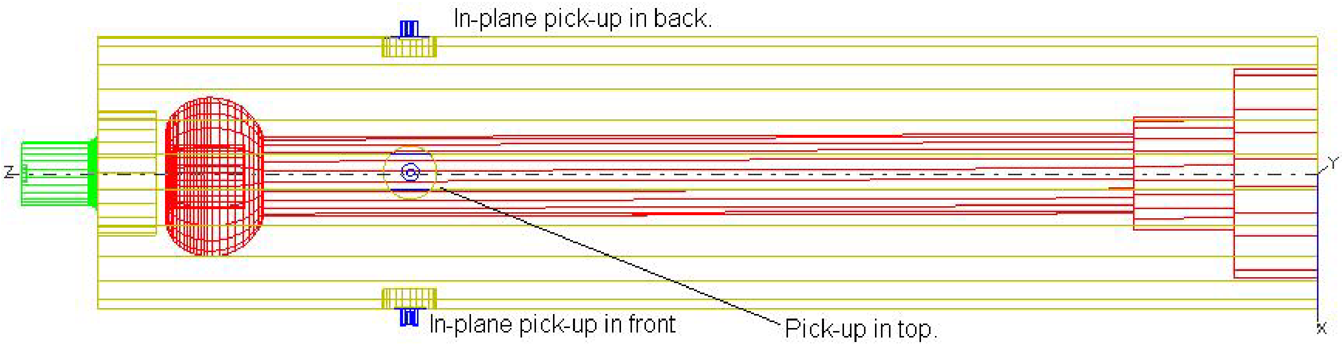
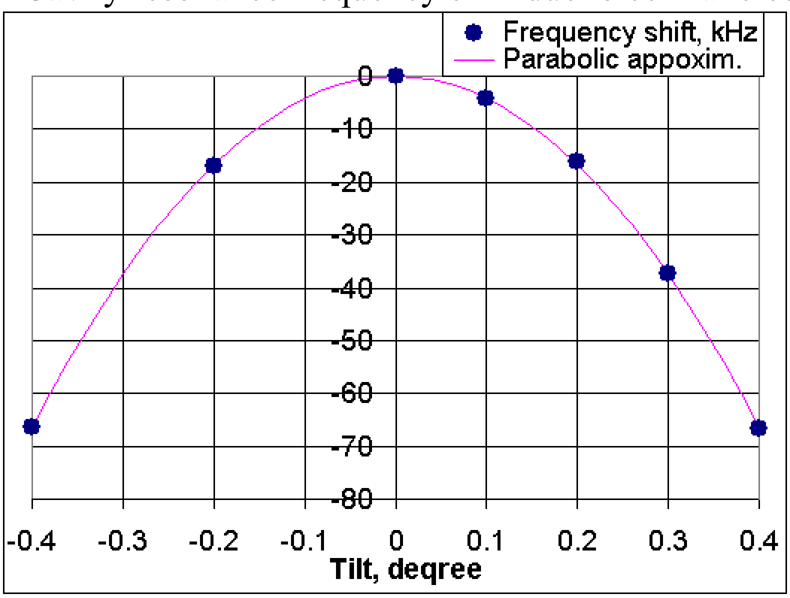


Fig16. Ansys simulations of mechanical vibrations of central electrode. Lowest frequency mode mechanical resonance at F=35.2Hz.



Cavity resonance frequency shift due to central electrode tilt.



$\Delta F = -416 * \alpha^2$, kHz

α – tilt, degree

$\Delta F = -0.89 * \Delta X^2$, kHz

ΔX – shift, mm

If X0 initial tilt:

$\Delta F = -1.78 * X0 * \Delta X$, kHz

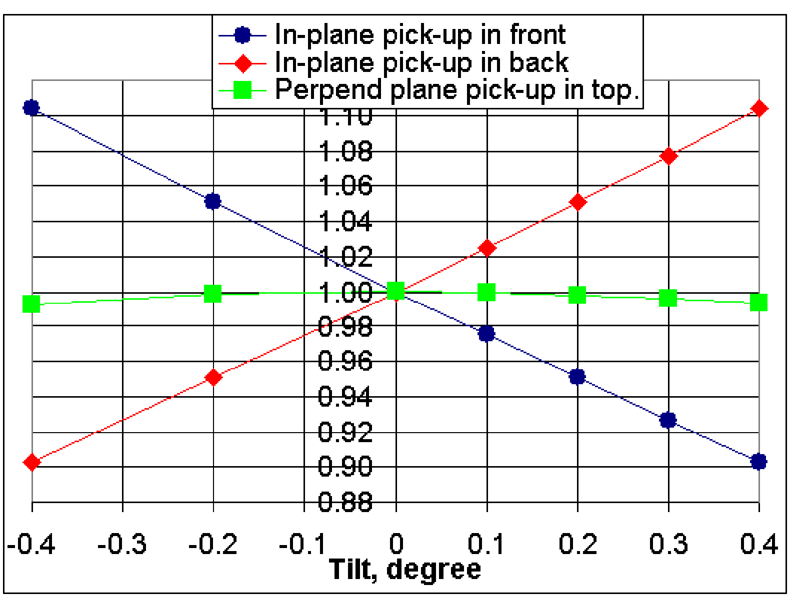
So, mechanical vibrations cause resonance frequency modulation of the cavity or phase modulation:

$$d\varphi = \frac{-2dF}{F(1+Q^2(2\Delta F/F))}$$

And amplitude modulation:

$$\frac{dA}{A} = \frac{-2Q^2\Delta F * dF}{F^2(1+Q^2(2\Delta F/F)^2}$$

Peak-up signals modulation due to central electrode tilt.



One more source of amplitude modulations:

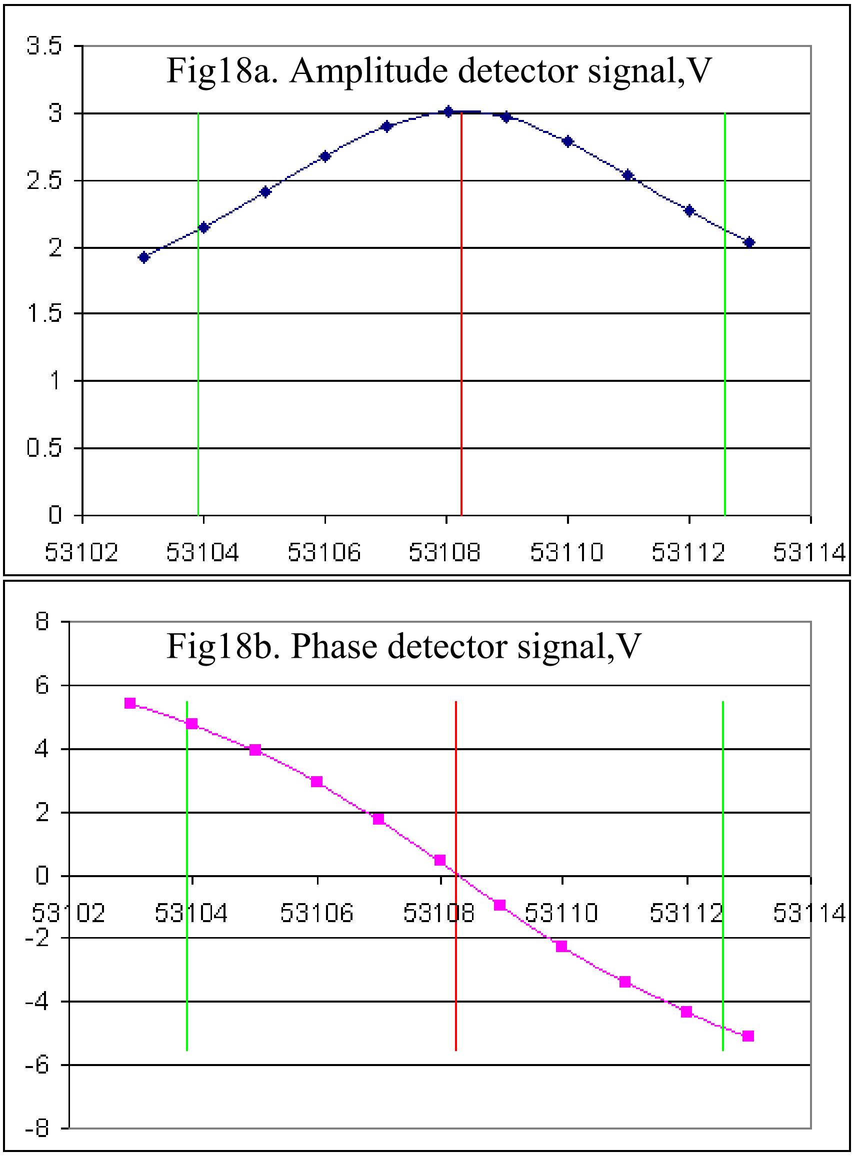
$$\frac{dA}{A} = 0.252 * \alpha,$$

α – tilt, degree

$$\frac{dA}{A} = 0.0117 * dX,$$

dX – shift, mm

Fig17. HFSS simulations cavity.



$$A = \frac{A_0}{\sqrt{1 + Q^2 \left(\frac{F}{F_0} - \frac{F_0}{F}\right)^2}}$$

$$\varphi = arctg\left[Q\left(\frac{F_0}{F} - \frac{F}{F_0}\right)\right]$$

Calculation from measurement data results:

Q=6120

F0=53.10825MHz

Phase detector sensitivity 9.4deg/V

Fig18. Measurements on different frequency with step 1kHz. These measurement allow to calculate F0 and Q of the cavity and phase detector sensitivity.

Amplitude modulation (fig13) on 31Hz –90dB corresponds to dX=2.7mkm of mechanical vibrations of cavity central electrode

Phase modulation (fig13) on 31Hz –45dB corresponds to .053 degree or 0.00093rad.

0.00093 rad correspond to dF=0.001*F0/2/Q=4.0Hz. And from HFSS simulations (fig17) can be estimated offset for cavity central electrode: X0=dF/1.78/dX=0.004/1.78/0.0027=0.83mm.

Geo sensors data for 31Hz –60dB, 0.001V. Sensitivity 45V/(m/sec). Mechanical vibrations amplitude calculated by formula:

$$dX = U / 45 / (2\pi F)$$

dX=0.11mkm outside of the cavity.

Proposals:

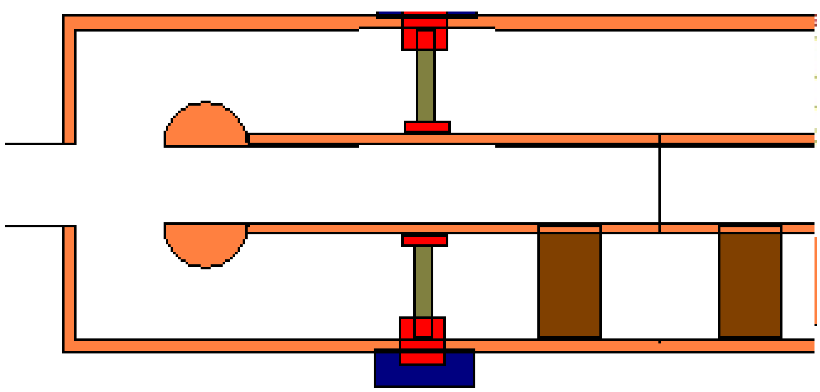
1. Remove additional sources of mechanical vibrations. For example, insulate mechanically water heaters from cavity(fig4).

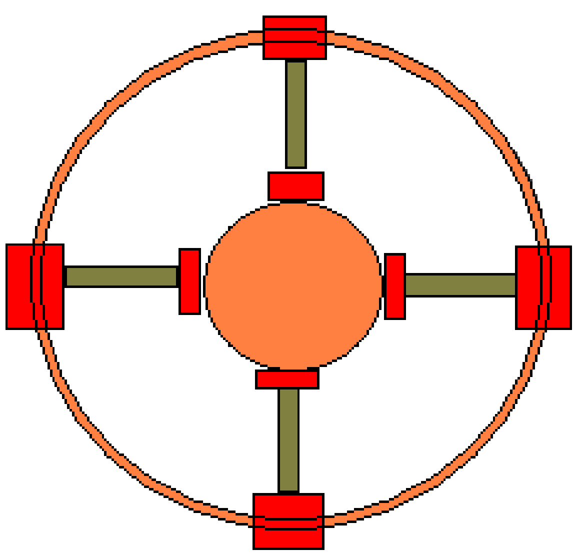
2. Install additional peak_up antenna opposite side of the cavity and use the sum of signals from 2 opposite peak_ups for reducing amplitude modulations (fig17).

3. Align cavity central electrode to reduce resonance frequency modulations of the cavity. To control alignment process can be used spectral analysis (fig13) and correlation analysis (fig15)

4. Increase rigidity of the central electrode to increase mechanical vibrations resonance's above synchrotron frequency 34Hz.

5. 3 and 4 can be done by adding 4 supports 0.6-0.7m apart from cavity center. 8 per cavity:





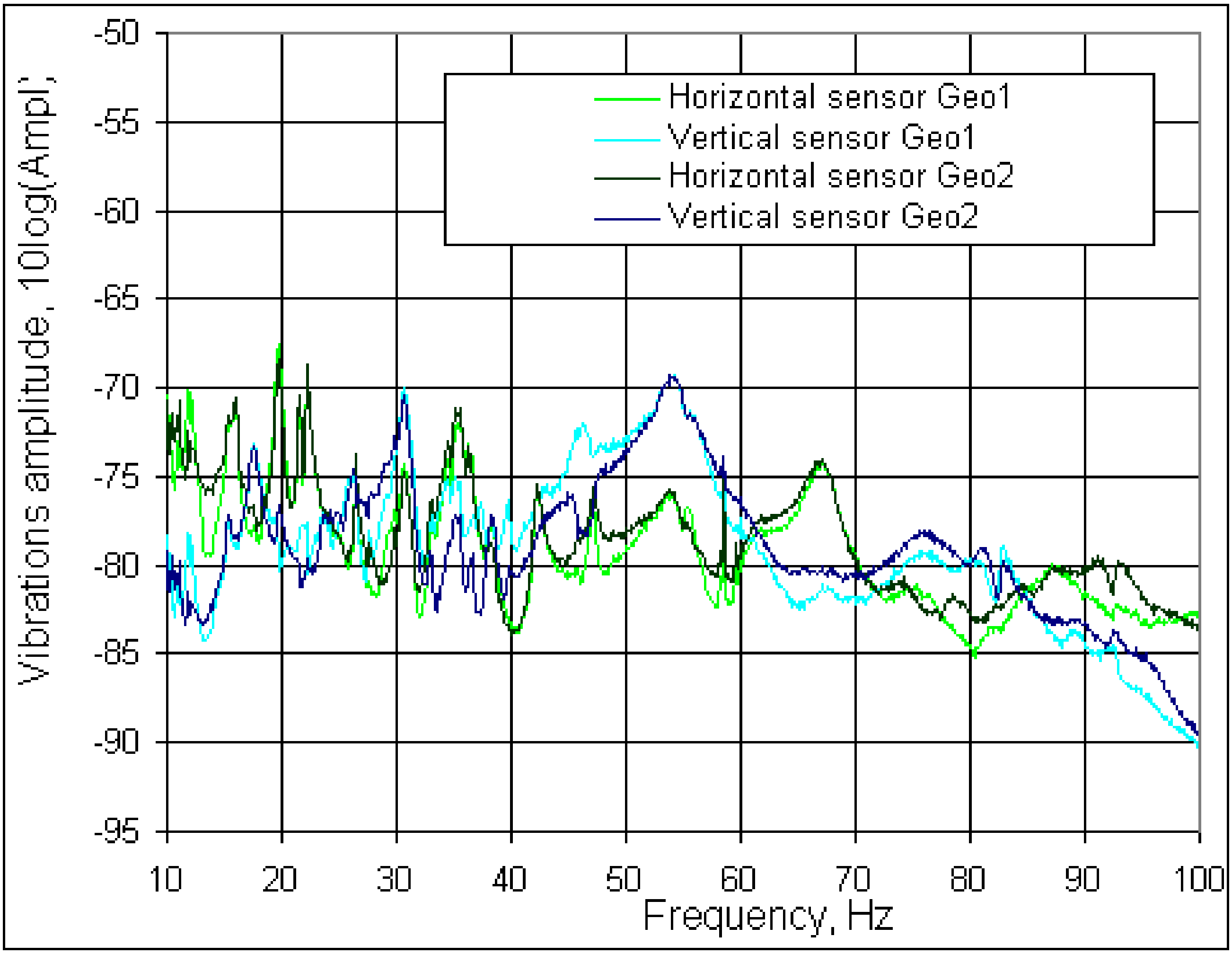


Fig19. Station2 cavity outside surface mechanical vibrations spectrum. Logarithmic scale. –60dB correspond to 1micron of amplitude, -70dB to 0.1 micron of amplitude.